# Change of meteorological conditions in Siberian cities under the effect of anthropogenic factor

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Based on data of eight-time daily meteorological observations (during 1981–1985) in one of Siberian cities (Kemerovo) and at several points, at the distances of several tens kilometers from Kemerovo, the study has been performed of the effects of the anthropogenic factor on the fields of air temperature and humidity, as well as on the formation of fogs in the city. The close correlation between temperature variations and water vapor pressure (the correlation coefficients are, as a rule, no less than 0.60–0.70) and the weak correlation (the correlation coefficients from 0.05 to 0.10) between the temperature and the pollutant concentration (such as CO, $NO_2$, ammonia, dust) enable us to assume that the change of content of anthropogenic water vapor and the greenhouse effect caused by it are of crucial importance in the formation of heat island in the city. Higher temperatures favor the decrease of the fog occurrence in the city as compared with its environs.

In recent decades the scientists from Siberian Branch of the Russian Academy of Sciences and researchers from the Federal Hydrometeorological Service have given considerable attention to the investigations into the ecological problems of Siberia. The latest papers presented here are the special thematic issues of *Atmospheric and Oceanic Optics*[1–3] as well as some monographs.[4–6]

As was noted in Refs. 7 and 8, the air basin of cities and large industrial centers differs from the environment not only by high levels of pollution but by significant differences in the field of temperature and air humidity, in the formation of fogs, hazes, and precipitation, to say nothing of the radiation fluxes, wind velocity, and so on.

Deviations of temperature and air humidity in a city from their values in the unperturbed environment can have a pronounced effect on the economic activities and human health. It is a common knowledge that a 1°C increase in the air temperature in the city can cause an increase in the probability of cardiovascular diseases by several times. The phenomena caused by water vapor condensation, namely, hazes, fogs, and different types of precipitation can essentially affect the economic activity of people.

Worsening of the visibility due to the above phenomena has an essential effect on the work of all types of transport (aviation, automobile, river, sea). Humidity and precipitation are most important factors governing the state and durability of houses, roads, and directly the human health (sharp increase of traumas under icy conditions of roads). Until so far, the meteorological regime of St. Petersburg and its environs has been investigated most thoroughly.[8,9]

It is of certain interest to apply the methodology, results, and regularities, determined for the northwest of Russia, to the other regions and to study the generality of these regularities.

Below we present analysis of the observation data compiled during 1981–1985 in Kemerovo (K), the city with the population more than 700,000 people and highly developed industry and transport. The data of this analysis are compared with the characteristics of meteorological conditions in two smaller settlements, Barzas (B) and Topki (T) that are at a distance of 100 km from Kemerovo to the southeast and 45 km to the northwest, respectively. Practically, the state of the atmosphere over these settlements does not differ from the background one unaffected by the anthropogenic factors.

## Temperature and humidity of the air

Processes, under the action of which the peculiarities of the meteorological conditions of the city are formed, refer to the number of mesoscale ones. To exclude the influence of the processes of synoptic and larger scales, we analyze not the temperature ($T$), water vapor pressure ($e$), and the relative humidity ($f$) themselves, but the following their differences:

$$\Delta T_i = T_K - T_i, \;\; \Delta e_i = e_K - e_i, \;\; \Delta f_i = f_K - f_i,$$

where $T_K$, $e_K$, $f_K$ are the values of $T$, $e$, $f$ in Kemerovo; $T_i$, $e_i$, $f_i$ are the values observed in Barzas ($i = 1$) and Topki ($i = 2$).

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**Table 1. Monthly mean and seasonal differences of temperature ($\Delta T$, °C), water vapor pressure ($\Delta e$, hPa), and relative humidity ($\Delta f$, %)**

| Differences | December | January | February | Winter | June | July | August | Summer |
|---|---|---|---|---|---|---|---|---|
| $\Delta T_1$ | 2.2 | 0.9 | 1.3 | 1.5 | 2.4 | 1.5 | 2.4 | 2.1 |
| $\Delta T_2$ | 2.1 | 1.2 | 1.7 | 1.7 | 2.0 | 1.2 | 1.6 | 1.6 |
| $\Delta e_1$ | 0.2 | 0.9 | 0.1 | 0.4 | 2.5 | 1.2 | 1.7 | 1.8 |
| $\Delta e_2$ | 0.2 | 0.1 | 0.1 | 0.1 | 1.2 | 2.6 | 2.0 | 1.9 |
| $\Delta f_1$ | –5 | –3 | –3 | –4 | –6 | –4 | –3 | –4 |
| $\Delta f_2$ | –4 | –2 | –2 | –3 | –7 | –3 | –2 | –4 |

According to data given in Table 1 the air temperature in Kemerovo both in winter and in summer is higher than in the surrounding medium. The mean monthly values of the difference $\Delta T$ are from 0.9 to 2.2°C in winter and from 1.2 to 2.4°C in summer. In the city the water vapor content is higher; based on the mean monthly values, the vapor pressure in Kemerovo is higher than in Barzas and Topki (from 0.1 to 0.9 hPa in winter and 1.2 to 2.6 hPa in summer).

Burning all kinds of fuel (coal, oil, natural gas, firewood) produces a great amount of water vapor along with carbon dioxide ($CO_2$) and monoxide (CO), and other gaseous and solid impurities (for example, burning of 1 kg of gasoline yields 1.3 kg of $H_2O$, and burning of 1 kg of natural gas yields 1.2 of water vapor[9]). Clearly, the water vapor emitted into the atmosphere increases the water vapor content in the city as compared with its content in the countryside. As a result, all the values of $\Delta e > 0$.

Since the negative $\Delta e$ are lacking, another factor, i.e., the difference in the character of underlying surface and the produced difference in the evaporation rate in the area of Kemerovo is not of crucial importance as, e.g., in St. Petersburg[9] where the values of $\Delta e < 0$ can be observed during daytime in summer.

The relative humidity $f = e/E(T)$ depends not only on the water vapor pressure $e$, but also on temperature $T$. Therefore, with the growth of $T$ the saturated vapor pressure $E(T)$ increases, and $f$ decreases. From Table 1 it follows that the growth of air temperature affects the relative humidity $f$ more strongly than the increase in water vapor pressure $e$. In this case the values of $f$ in Kemerovo are several percent less than in Barzas and Topki.

The question on the temperature rise of air in the city as compared with the surrounding medium was studied extensively based on the data of Kemerovo (K) and the settlement Novostroika (N) 20 km to the south from the center of the city. Based on the data of observations obtained at 9, 15, and 21 (local time) in 1977, we determined not only the repetition, mean values, and root-mean-square deviations, but also constructed the distribution $\Delta T = T_K - T_N$ and $\Delta e = e_K - e_N$. Omitting analysis of these characteristics, which confirm, on the whole, the regularities previously revealed in the European part of Russia[9] and use these characteristics to assess the role of different factors in the formation of the heat island in the cities.

Table 2 presents the correlation coefficients $r_{\Delta T,\Delta e}$ between the differences of $\Delta T$ and $\Delta e$ as well as the volume $N$ of the data sample used. These coefficients are close to those obtained for the differences $\Delta T$ and $\Delta e$ between St. Petersburg and its surroundings: according to Ref. 9 the seasonal values of $r_{\Delta T,\Delta e}$ at different times (from 1975 to 1980) vary between 0.45 and 0.75 in winter and between 0.27 and 0.63 at night in summer. At daytime in summer, due to sharp distinction in the evaporation rates (exceeding the effect of anthropogenic emissions of water vapor), the values of the correlation coefficients $r_{\Delta T,\Delta e}$ are much less than at night (even the values $r < 0$ can appear).

**Table 2. Correlation coefficients between the differences of $\Delta T$ and $\Delta e$ in Kemerovo and Novostroika in 1997**

| Correlation coefficients | Spring | Summer | Fall | Winter |
|---|---|---|---|---|
| $r_{\Delta T,\Delta e}$ | 0.37 | 0.59 | 0.58 | 0.62 |
| $N$ | 213 | 229 | 227 | 212 |

For the area of Kemerovo it was impossible to assess the values of the correlation coefficients $r_{\Delta T,\Delta e}$ for daytime and nighttime (because no nighttime observations in Novostroika were carried out). However, seasonal differences in the values of the correlation coefficients $r_{\Delta T,\Delta e}$ are manifested in this case: in spring the values of $r_{\Delta T,\Delta e}$ are much less than in other seasons. Having used the known formula $\sigma_\tau = (1 - r^2)/\sqrt{N}$, we obtain the following estimates of the errors of calculations of the correlation coefficients $r$ given in Table 2: $0.04 < \sigma_r < 0.06$.

Since, along with the water vapor, the effective radiation is absorbed by the other gaseous and solid contaminants emitted to the urban atmosphere, it is of interest to estimate the role of these contaminants in the increase of the urban air temperature. Unfortunately, we had at our disposal only the data on the concentrations of several contaminants (CO, $NO_2$, $NH_3$, and dust), although other gaseous contaminants (such as $CO_2$, $O_3$, NO, $N_2O$, $CH_4$) also affect the effective radiation.

Based on the data available on the measured concentrations ($q$) of the contaminants, made in 1997, we calculated the seasonal correlation coefficients $r_{\Delta T,q}$ between the difference $\Delta T = T_K - T_N$ and the concentration $q$ of contaminants in Kemerovo (Table 3).

**Table 3. Seasonal correlation coefficients $r_{\Delta T,q}$ between differences of the temperature ($\Delta T = T_K - T_N$) and the concentration $q$ of contaminants in Kemerovo (sample volumes are from 133 to 228)**

| Contaminant | Spring | Summer | Fall | Winter |
|---|---|---|---|---|
| Carbon oxide | –0.07 | 0.07 | –0.08 | 0.01 |
| Nitrogen peroxide | 0.02 | 0.05 | 0.05 | 0.03 |
| Ammonia | –0.07 | 0.19 | –0.08 | 0.04 |
| Dust | –0.27 | 0.03 | –0.07 | 0.02 |

The comparison between data presented in Tables 2 and 3 shows that the contribution from the absorption of effective radiation to temperature variations $\Delta T$ by all the contaminants is negligibly small as compared with the contribution from its absorption by water vapor: most of the values of the correlation coefficient $r_{\Delta T,q}$ is by one or two orders of magnitude less than the values of $r_{\Delta T,\Delta e}$ (only for ammonia in summer $r_{\Delta T,q}$ is approximately three times less than $r_{\Delta T,\Delta e}$, and the coefficient $r_{\Delta T,q}$ for the dust, although it can be compared with the values of $r_{\Delta T,\Delta e}$, but it is less than zero; the increase of dust content is followed by cooling of the atmosphere). We think that such a result is physically understandable: whatever the absorptivity of any contaminant may be, the energy of absorbed radiation is proportional to the contaminant concentration. This concentration, even for the carbon monoxide (CO), whose content is larger among that of all other contaminants, does not exceed $10^0 - 10^1$ mg/m$^3$, while the absolute humidity (water vapor concentration) is on the order of $10^{-1}$–$10^1$ g/m$^3$, i.e., by 100–1000 times greater than the CO content.

For a comparison we present the data on the correlation between $\Delta T$ and $\Delta e$, on the one hand, and $\Delta T$ and $\Delta q$, on the other hand, estimated by the four-time measurements of the values $T$, $e$, and $q$ in St. Petersburg and $T$ and $e$, in the Sosnovo in 1991 (Table 4). From these data one can draw the same conclusion as from Tables 2 and 3.

**Table 4. Correlation coefficients $r_{\Delta T,\Delta e}$ and $r_{\Delta T,q}$ (sample volumes during 24 hours – from 170 to 283)**

| Correlation coefficient | Winter | | | Summer | | |
|---|---|---|---|---|---|---|
| | Day | Night | 24 hours | Day | Night | 24 hours |
| $r_{\Delta T,\Delta e}$ | 0.72 | 0.81 | 0.79 | –0.10 | 0.35 | 0.15 |
| $r_{\Delta T,q}$ CO | 0.10 | 0.11 | 0.11 | 0.02 | –0.04 | 0.01 |
| $r_{\Delta T,q}$ $NO_2$ | –0.03 | 0.09 | 0 | –0.02 | 0.16 | 0.08 |

However, this conclusion refers only to the contaminants under study and it cannot be used for all other gaseous impurities without an additional study.

In any case, the above results point to the necessity of more thorough analysis of the role of anthropogenic water vapor in changing the temperature, especially, total temperature. It should be mentioned that the low-level clouds have a pronounced effect on the radiation balance of the atmospheric boundary layer. The low-level cloud amount increased in recent 20 years by 3%.[10] Therefore, when solving the problem of the climate warming, it is also necessary to concentrate on the investigation of the low-level cloud field.

## Fog

The pollution of the urban atmosphere by the industrial products, the change of temperature and air humidity, wind velocity, radiation fluxes, characteristics of underlying surface, etc., have a marked effect on the conditions of the formation of such important phenomena as fogs. After the publication of papers 7 and 8 it was clear that the widely accepted in the past opinion[1,2] about more favorable conditions of the formation of fogs in the cities, as compared with the countryside, should be rejected as contradictory to the factual data.

It follows, in particular, from Table 5 containing the values of the relations between the number of days with fog in the settlements of Barzas and Topki and the number of same foggy days in Kemerovo. In fact, the occurrence of fogs in Kemerovo (K) is well below than that in the settlements of Barzas (B) and Topki (T): by a factor of 2.50 and 1.73 – in summer and by a factor of 1.53 and 2.18 – in winter. The relations between the fog duration in Barzas and Topki and the fog duration in Kemerovo are: B/K – 1.25 and 2.42; T/K – 0.87 and 3.10 in summer and winter, respectively.

**Table 5. Relation between the number of days with fog in Barzas and Topki and the number of foggy days in Kemerovo in 1981–1985**

| Relation | Fog | | Translucent fog | |
|---|---|---|---|---|
| | Winter | Summer | Winter | Summer |
| B/K | 1.53 | 2.50 | 1.50 | 2.29 |
| T/K | 2.18 | 1.73 | 1.83 | 1.31 |

It might be of interest to consider such fog characteristics as the number of days with fog and the fog duration as compared with the total number of days in the season and the net duration of the season (see Table 6). It is seen from this table that the number of days with fog, as compared with the total number of days in the season, varies in winter – between 5% in Kemerovo and 8–11% in Barzas and Topki, and in summer – between 11% in K and 18–26% in T and B.

**Table 6. Number of days with fog and the fog duration as compared with the total number of days and the overall duration of the season**

| Point | Winter | | Summer | |
|---|---|---|---|---|
| | Number of days | Fog duration | Number of days | Fog duration |
| Kemerovo | 0.051 | 0.0018 | 0.106 | 0.025 |
| Barzas | 0.078 | 0.0042 | 0.265 | 0.033 |
| Topki | 0.111 | 0.0047 | 0.183 | 0.022 |

The latter ratio, presenting the probability of the fog existence, is much less than the former one. It varies: in winter – between 0.2% in Kemerovo and 0.4–0.5% in Barzas and Topki, and in summer – between 2% in K and 2–3% in B and T.

From Table 6 it follows that fogs may appear in summer more frequently than in winter. This conclusion is based on the number of days with fog: the increase from 1.6 to 3.4 times is observed, in the case of the probability of the existence – the increase from 4.7 to 13.9 times is observed. This is accounted for by the fact that in winter in Siberia, as a whole, the anticyclonic conditions prevail (the mean value of pressure in Kemerovo is 1013.1 hPa) while in summer the cyclonic conditions prevail (the pressure in Kemerovo is 9.4 hPa lower than in winter). These data refute a statement on more favorable conditions of the formation of fogs in anticyclones and simultaneously confirm the results obtained by modeling: the fogs are formed mainly in the areas of low pressure with typical ascending flows.

Now we consider such a characteristic as the mean time (in hours) of the fog existence during a day with fog. In Kemerovo the mean time is 5.66 and 0.84 in summer and winter, respectively, in Barzas– 2.99 and 1.29, in Topki – 2.83 and 1.02.

The main reason for the decrease of fogs in a city is the air temperature rise. To derive an expression for varying the fog water content, we turn to the formula for its volume (absolute) water content[13]

$$\delta = a - a_m(T), \quad (1)$$

where $a$ is the moisture content in the fog (per 1 m$^3$) and $a_m(T)$ is the absolute humidity in the saturation state.

The change of moisture content mainly follows the change of water vapor partial pressure. Then, according to Ref. 13, $\Delta a = 273/T\,\Delta e$. If we use the Clasius–Clapeyron equation $\Delta a_m(T) = [La_m/(R_n T^2)]\,\Delta T$, then, based on Eq. (1) and the last two relations, we obtain the following expression for the fog water content increase if the water vapor pressure varies by $\Delta e$ and the air temperature varies by $\Delta T$:

$$\Delta\delta = 217/T\,\Delta e - b\Delta T, \quad (2)$$

where $\Delta e$ is measured in hPa, $\Delta T$ – in K, and the coefficient $b$ takes the following values:

**Coefficient *b***

| $T$, °C | –25 to –15 | –15 to –5 | –5 to 5 | 5 to 15 | 15 to 25 |
|---|---|---|---|---|---|
| $b$, g/(m$^3$·K) | 0.087 | 0.184 | 0.363 | 0.661 | 1.119 |

The estimates show that in most cases in Eq. (2) the second term is of considerable importance. It is clear that at $T$ higher than –5°C the temperature rise of 0.5°C results in a water content decrease from 0.18 to 0.55 g/m$^3$. Since the water content of fogs under real conditions does not exceed, as a rule, $10^{-1}$–$10^0$ g/m$^3$, the increase of $T$ in the city even by 0.3–0.5°C results in the disappearance of fogs with low water content (weak and, partially, moderate).

Finally, the following conclusions can be drawn:

1) the absorption of effective radiation by water vapor is of crucial importance in the formation of the heat island in the city: the effect of other gaseous and solid impurities in the urban air temperature rise considered here is by one or two orders of magnitude lower;

2) the absolute humidity increases in the city (as compared with the countryside) under the action of anthropogenic water vapor emissions;

3) the temperature rise results in a reduction of the relative humidity, water content, and fogs, and, as a consequence, in the decrease of the number and duration of the fogs in the city as compared with the countryside;

4) when investigating the problem of change of the temperature (climate) in large areas and on the global scale special attention must be given to the assessment of the effect of humidity fields and clouds on the radiation fluxes.

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